(Chapter in forthcoming book: Hazards Due to Comets and Asteroids"; Univ. of Arizona Space Science Series)

Predicting Close Earth Approaches of Asteroids and Comets

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Abstract

The motions of all known Earth approaching asteroids and comets with reasonably secure orbits have been numerically integrated forward in time to A.D. 2200. Special care was taken to use the best available initial conditions including orbits based upon radar data. Each object was integrated forward with Earth and moon perturbations treated separately, with general relativistic equations of motion and with perturbations by all planets at each integration step. For the active short-period comets whose motions are affected by the rocket-like effects of vaporizing ices, a nongravitational force model was employed. When a close approach to the Earth was sensed by the numerical integration software, an interpolation procedure was used to determine the time of the object's closest approach and the minimum separation distance at that time. For those objects making the closest Earth approaches in the next two centuries, an error analysis was conducted to determine whether or not the object's error ellipsoid at the time of closest approach included the Earth's position (i.e., an Earth collision could not be ruled out). Although there are no obvious cases where a known near-Earth asteroid or comet will threaten the Earth in the next two centuries, there area few objects that warrant special attention, The Aten type asteroid 2340 Hathor makes repeated close Earth approaches and because most of its orbit lies within that of the Earth, it is often a difficult object to observe in a dark sky. For both asteroids and comets, there are generally dramatic increases in their position uncertainties following close planetary encounters.

Because of their short observational data intervals, their unmodeled nongravitational effects, and the possibility of escaping early detection by approaching the Earth from the sun's direction, long-period comets may present the largest unknown in assessing the long-term risk of Earth approaching objects. Fortunately the frequency with which these objects approach the Earth is very small compared with the numerous approaches by the population of near-Earth objects with short periodic orbits. For the short-period comets, rocket-like outgassing effects and offsets between the observed center-of-light and the comet's true center-of-mass can introduce large uncertainties in their long-term orbital extrapolations. The uncertainty in the future motion of an active short-period comet is substantially larger than the motion of an asteroid with a comparable observational history. While asteroids dominate the list of close Earth approaches in the next two centuries, their motions are relatively predictable when compared to the active comets.

For the rapidly growing population of known near-Earth asteroids and comets, efficient procedures are suggested for monitoring their long-term motions thus allowing early predictions of future close Earth approaches.

I. Introduction

Collisions of asteroids and comets with the Earth is a topic so provocative and so prone to sensationalism that great care must be taken to assess the realistic hazards in the near future. The task of accurately predicting future close Earth approaches by known near-

Earth objects is essential for risk assessment studies. As the discovered population of near-Earth objects continues to grow, and the orbit determinations of previously known objects continues to improve, the motions of these objects should be routinely integrated forward for a few hundred years to investigate their orbital behavior. Note should be made of objects that can pass the Earth closely so they can be placed upon the "short list" of objects for which additional attention is required. In this fashion, possible Earth threatening objects can be identified well in advance so that future astrometric observations can be scheduled. Once this short list of close Earth encounters has been compiled, error covariance analyses should be undertaken for each object to determine whether or not the object's position error ellipsoid includes the Earth's position at the time of the closest' approach (i.e., an Earth - object collision cannot be ruled out). For the closest Earth approaches, impact probabilities should be computed in a realistic fashion. If useful risk assessments are to be conducted, future close Earth approach predictions for asteroids and comets must be accompanied by error analyses and impact probabilities.

The accurate prediction of asteroid and comet close Earth approaches is also necessary for planning future ground-based and space-based observation programs for these scientifically interesting objects. Given the very low probability of finding a truly threatening future encounter, this latter use of close approach predictions is, perhaps, of more immediate use.

In section 2, we briefly discuss the benefit of studying near-Earth objects when they are, in fact, near the Earth. Section 3 outlines the necessary steps for accurately monitoring the long-term numerical motions of near-Earth objects and presents the results of our numerical integrations to the year A.D. 2200 for all known near-Earth objects with reasonable orbits. Section 4 addresses the problems of trying to accurately predict the motions of some near-Earth objects and presents error analyses for those objects making the closest Earth approaches. Section 5 presents a summary and our main conclusions.

II. The Importance of Near-Earth Approaches by Asteroids and Comets

Because the signal to noise ratio for an observation of a asteroid or comet depends upon the inverse square of the topocentric distance, efforts have been made to conduct physical studies of these objects during close Earth approaches. This is especially true for radar observations because the signal to noise ratio is proportional to the inverse fourth power of topocentric distance (Ostro 1993). While the physical study of near-Earth objects during close Earth approaches is an obvious course to pursue, it is not as obvious how important astrometric observations are during these close Earth approaches. To a reasonable approximation, the power, or benefit, of optical astrometry improves linearly with the decreasing distance between the observer and the target object.- Position measurements of an object that are accurate to one arc second at a distance of 1.0 AU and 0.1 AU represent linear plane-of-sky errors of about 725 km and 72.5 km respectively.

At close Earth approaches, radar astrometric observations can provide extremely powerful data for orbit improvement (Yeomans and Chodas 1987; Ostro et al. 1991; Yeomans et al. 1992). These radar Doppler and time delay measurements have far greater fractional precision than optical astrometric data but can only be taken during close Earth approaches. The ability of radar data to reduce future ephemeris errors is most dramatic for newly discovered objects for which only short optical data intervals are available. For objects whose optical data intervals include several returns to opposition, their orbits are well defined even in the absence of radar data. The ideal data set for a near-Earth object includes the combination of optical astrometric data (plane-of-sky data) over long time intervals and precise radar measurements (line-of-sight data) during close Earth approaches. Orbits that include radar data as well as optical astrometric data can be more accurately extrapolated into the future when compared with a similar orbit that is based upon only the optical data. As an example, an error analysis has been used to demonstrate the power of radar observations in reducing the ephemeris prediction error for minor planet 4179 Toutatis. As is evident from Figures 1 and 2, Toutatis made a close Earth approach in December 1992 and will make an even closer Earth approach in September 2004. During the December 1992 Earth approach, 34 time delay (range) and 21 Doppler (range rate) observations were made during the interval from November 27 through December 18. Employing an error covariance analysis similar to that described by Yeomans and Chodas (1987), one sigma error ellipses were computed in the Toutatis orbit plane at the time of the Earth close approach on September 29, 2004. Figure 3 displays two error ellipses, the smaller one representing the expected one sigma position errors resulting from processing all optical observations (1934 - 1992) and the late 1992 radar data. To account for unmodeled error sources, the optical data were given noise values intentionally larger than the rms residuals from the orbit determination process. A data noise of 2 arc seconds was used for the two observations in 1934 while the remaining optical data (1988 - 1992) were assigned noise values of 1.3 arc seconds. The radar delay observations were given a noise value of 15 micro seconds (1.5 km) while the Doppler observations were assigned a value of 1 Hertz (1.8 cm/s for a frequency of 8510 MHz). The larger error ellipse in Figure 3 represents the one sigma position errors resulting from the processing of the optical data alone, Assuming no new astrometric observations are considered, the position errors for 4179 Toutatis during the 2004 close Earth approach will be nearly five times smaller as a result of the 1992 radar data.

Spacecraft mission planners have often taken advantage of close Earth passages to design low cost flyby and rendezvous missions to comets and asteroids. A spacecraft encounter that takes place near Earth ensures a short communication distance, drives down the ephemeris uncertainties of the target object and allows excellent ground-based studies that nicely complement the in-situ spacecraft observations. By selecting near-Earth object targets that have low orbital eccentricities, low inclinations and perihelia near 1.0 AU, transfer trajectories can be found that require only very modest energy requirements (McAdams 1991). As a crude rule of thumb, the easiest near-Earth objects to reach for rendezvous missions are those objects whose orbital characteristics are most like that of the Earth itself. An example of an asteroid flyby mission that will take advantage of a close Earth approach is the Deep Space Program Science Experiment (DSPSE) that is scheduled to fly within 100 km of asteroid 1620 Geographos six days after the asteroid passes within 0.025 AU of the Earth in late August 1994 (Yeomans 1993).

III. Long Term Predictions of Near-Earth Encounters

In an effort to establish the close Earth approaches of known objects in the next two centuries, the orbits of the near-Earth objects have been numerically integrated forward to the year 2200. Those asteroids whose perihelion distances are currently 1.3 AU or smaller and whose orbits are secure were selected for the integration process. Because comets often suffer large planetary perturbations, every periodic comet was included in our integrations, regardless of its perihelion distances, For the long-term integrations, whose results are presented in Table 2, initial orbits were considered secure if astrometric data existed for two or more apparitions. Some asteroids with single apparitions were also included if radar observations were available or if the optical data interval exceeded six months. For the short-term results displayed in Table 1, these criteria were relaxed somewhat; this latter group consisted of 172 asteroids and 145 periodic comets.

A. Description of numerical integrations to A.D. 2200

One of us (PWC) developed a special integration package whereby each object is sequentially integrated forward to a given time with orbital elements automatically output near the time of each perihelion passage. The most recent orbital information for each object was used to initialize these integrations. In addition, many near-Earth objects have orbits improved with radar data as well as the optical data (Yeomans et al. 1992) and when appropriate, these radar-based orbits were used to initialize the long-term integrations.

Once the integration of an object is underway, the step size is adjusted to maintain a local velocity error of less than 10^{-13} AU/day. The Jet Propulsion Laboratory Development ephemeris, DE 200 (Standish 1990) was used throughout for the planetary perturbations that were computed at each time step. The outer planetary masses in DE200 were updated to include those values resulting from the Voyager spacecraft flybys, A special interpolation scheme is invoked each time the integrator senses a planetary close approach and if an object's orbit were perfectly known, close approach times would be accurately output to the one minute level. Depending upon the accuracy of an object's initial orbital elements, the error in the actual close approach time may be considerably larger.

General relativistic equations of motion were employed for all objects and the perturbations by the Earth and moon were considered separately rather than treating their combined masses as being located at the barycenter. However, we have yet to include the perturbative effects of some of the larger asteroids when integrating the near-Earth objects.

The general relativistic advancement in the line of apsides is an important consideration for objects whose eccentricity is large and whose semi-major axis is small. For each period, the advancement in the line of apsides is approximately $0.038/a(1-e^2)$ arc seconds where e is the eccentricity of the object's orbit and a is the semi-major axis in AU. As an example, we note that for the four asteroids with the largest relativistic advances in their lines of apsides, 3200 Phaethon, 1566 Icarus, 2100 Ra-Shalom, and 2340 Hathor, the perihelion advance in 200 years amounts to 20.1, 19.9, 14.9, and 14.6 arc seconds respectively. To maintain consistency in the integration of asteroid and comet equations of motion, one should include general relativistic effects to account for the relativistic advancement in the lines of apsides, but more importantly the JPL planetary ephemerides most often used for asteroidal and cometary orbit determinations (DE1 18, DE200 etc.) were created using relativistic equations of motion. The use of the JPL planetary ephemerides and non-relativistic equations of motion for a comet or asteroid will necessarily introduce an error in the asteroid or comet's mean motion that is by no means negligible. This error is most noticeable when a correct, relativistic orbit is integrated forward or backward in time and then compared with an integration initialized with the same orbit but whose equations of motion are non-relativistic.

For objects making close Earth encounters, the Earth and moon perturbations must be treated separately, In extreme cases, a satisfactory orbit cannot be computed without separating the Earth and moon perturbations, For example, asteroid 1991 VG passed within 0.0031 AU of the Earth on Dec. 5.4, 1991 and within 0.0025 AU of the moon on Dec. 6.9. There are observational data on either side of this close approach. The orbital solution for 1991 VG was not successful until we abandoned the approximation of having the combined Earth and lunar masses located at the Earth-moon barycenter.

Although we did not consider the perturbations of some of the larger asteroids (e.g., Ceres, Pallas, and Vesta), these effects will be included in a future version of the JPL integration package, However, we note that the relative velocity difference between a perturbing asteroid and a near-Earth object will be relatively high so that these perturbations will rarely become important,

B. Tabular information on close Earth approaches

Table 1 presents the asteroids and comets making close Earth approaches to within 100 lunar distances (0,257 AU) within the interval Jan. 1, 1993 through Jan. 1,2001 and Table 2 presents the same information for those objects that came within 10 lunar distances (0.0257 AU) during the interval 2001-2200. Table 3 lists the few cometary close Earth approaches (to within 50 lunar distances) over the interval 1993-2200, Table 1 is primarily for planning future astronomical observations while Tables 2 and 3 address the issue of risk from near-Earth objects in the next two centuries. In Tables 2 and 3, in addition to the Earth close approach distances, the approximate minimum distance between the orbits of the object and the Earth are given in parentheses using a method described by Porter (1952). These latter distances are the closest that an object could be expected to approach the Earth if it were to arrive at just the right time.

Tables 1,2, and 3 should be inserted here.

IV. Error Analyses and Impact Probabilities for Close Earth Approaches

A. Error analyses for closest Earth approaches

For a few of those objects in Tables 2 and 3 making particularly close Earth close approaches, an error covariance analysis was undertaken along the lines outlined by Yeomans and Chodas (1987) to estimate the object's ephemeris uncertainties at the time of the close Earth approach. These analyses were carried out for the two asteroids making the closest Earth approaches (2340 Hathor and 4660 Nereus) and for the periodic comet making the closest Earth approach in the next century (Finlay). Although there were several asteroids making closer Earth approaches, the 2060 Earth approach (to within 0.05 AU) of comet Finlay is the closest cometary approach in the coming century. It was included in the error analyses computations because the outgassing effects of active comets can introduce orbital position uncertainties far larger than for asteroidal objects with comparable observation histories.

In an attempt to account for unmodelled error sources, observation noise values were purposely taken to be higher than the rms residual as determined from orbital computations. That is, despite the fact that modern astrometric observations of asteroids routinely achieve sub arc second accuracy, we gave each observation a noise value of 1.3" for the error analyses. Since no simulated, future data were considered in these analyses, the position uncertainties quoted in Table 4 represent the knowledge of the object's ephemeris given only the existing observations. With additional observations, the position uncertainties can be expected to shrink somewhat. In Table 4, the error estimates represent the uncertainty in the direction between the object and the Earth at the time of closest approach. For asteroids 2340 Hathor, 4660 Nereus, 4179 Toutatis, and comet Finlay, the existing orbits were updated using recent observational data, general relativistic equations of motion and treating the Earth, moon perturbations separately. These improved orbital elements were input into the long term integrations used to generate the information displayed in Tables 1 - 4.

Table 4. Earth close approach circumstances and associated position uncertainties for the three closest Earth approaches of asteroids as well as the closest cometary approach in the twenty first century.

Object	Date	Close Approach Distance	3-sigma Earth-object position uncertainty
4660 Nereus	2060 Feb. 14.3	0.0080 AU	21,000 km = 0.00014 AU
2340 Hathor	2069 Oct. 21.4	0.0066 AU	6,300 km = 0.00004 AU
2340 Hathor	2086 Oct. 21.7	0.0057 AU	335,000 km = 0.0022 AU
P/Finlay	2060 Oct. 27.0	0.0473 AU	412,800 km = 0.0028 AU

Because asteroid 4660 Nereus has a low inclination (i = 1.4 degrees) and a perihelion distance just inside the Earth's orbit, it makes rather frequent Earth approaches. The closest of these is in February 2060 and at that time the component of the 3 sigma position uncertainty ellipse that lies along the asteroid - Earth line is about 21,000 km and hence well short of including the Earth. That is, an Earth collision is ruled out.

The Aten asteroid 2340 Hathor makes a close Earth approach in October 2069 followed by another closer approach 17 years later (see Figures 4 and 5). As is evident from the information in Table 4 and Figure 6, the one sigma position uncertainties during the 2086 encounter are greatly increased as a result of the 2069 close Earth approach. Even so, the 3 sigma position uncertainty ellipse in 2086 does not include the Earth's position and a collision is again ruled out. From Figure 4, it becomes evident why Aten type asteroids like Hathor are so difficult to observe in a dark sky. Only 46 observations over the 1976-1983 interval were available for the orbit determination of 2340 Hathor.

Of the known short periodic comets, comet Finlay will make the closest Earth approach in the 21st century (see Figure 7). For the above error analyses for asteroids 4179 Toutatis, 4660 Nereus, and 2340 Hathor, the observational data noise (1,3 arc seconds) is the only assumed error source. For active comets like Finlay, there are also errors due to uncertain nongravitational effects and offsets between the comet's observed center-of-brightness and its true center-of-mass. The nongravitational effects are due to the rocket-like outgassing of the comet's nucleus and while these effects have been modeled (Marsden et al., 1973, Yeomans and Chodas, 1989), there remain significant uncertainties in the behavior of these effects over long time intervals. For comet Finlay, the center-of-light was assumed to be offset toward the solar direction with a value equal to 150 km at one AU and scaling with the inverse square of the heliocentric distance, We have assumed that the errors in the determination of the radial and transverse nongravitational parameters (Al, A2) are present but that we cannot solve for them; they are "consider" rather than "solve for" parameters. The Al and A2 nongravitational parameters were considered to be 100% and 10% uncertain respectively. At the time of the comet's close Earth approach on October 27, 2060 the 3 sigma error ellipse axes on the plane-of-sky are 783,000 km and 3,420 km. These axes would be 156,000 km and 3,050 km without the errors introduced by the nongravitational parameters and the offset between the comet's center-of-light with respect to its center-of-mass. If comet Finlay were an inactive asteroid, its position uncertainties would be substantially less.

B. Screening Potential Hazards as Near-Earth Objects are Discovered

As each new asteroid or comet is discovered, an efficient screening process must be undertaken to establish whether or not the new object has the potential for approaching the Earth closely, With only a few astrometric observations to work with over a short time span, the initial orbits of each discovered object will be so uncertain that very little can be said about its potential as a future hazard. Initially, it would be sufficient to compute the minimum distance between the orbits of the Earth and the new object to determine how close the object can approach the Earth. Marsden (1992) pointed out that for most of the near-Earth objects, a simple two-body computation using current orbital elements can be used to identify which objects <u>can</u> closely approach the Earth's orbit in the future, However, planetary perturbations can be effective in altering the current orbital parameters of a near-Earth object, so that perturbed numerical integrations are required to identify <u>actual</u> close Earth approaches in the future.

If the initial, or a subsequent, preliminary orbit indicates that an object could pass within, say, 0.2 AU of the Earth's orbit, the object would be assigned to the "A list" of objects for which a long-term ephemeris integration will be required when a sufficient number of observations were available for a perturbed orbit computation, To generate the information given in Tables 1-3, we simply selected those asteroids and comets with reasonable orbits and whose perihelion distances were less than 1.3 AU. Although a single planetary perturbation would not normally perturb the object's perihelion distance by more than 0.05 AU, a series of future perturbations might be expected to move an object's perihelion distance by that amount. In any case, with the increasing speed of modern-day computers, it would not be difficult to routinely integrate the motions of all near-Earth objects a few hundred years into the future and identify those objects making close Earth approaches (see Section **3).** Those objects that pass close to the Earth in the future would then be assigned to the "B list" whereby a covariance error analysis would be conducted to determine how close the object's error ellipsoid approaches the Earth anytime in the near future. Those few objects whose future error position ellipsoids lie within, say, 10 sigma of the Earth's distance at a close approach would be singled out for an impact probability computation. This screening process could be achieved in a straight forward fashion using efficient software with little intervention by the user except, perhaps, in the case where one close Earth approach is followed by another or when poorly modeled nongravitational forces render the motion of an active comet particularly uncertain.

C. Predicting Impact Probabilities

The probability that a close Earth-approaching asteroid or comet will actually impact the Earth can be approximated via a procedure which examines the position error ellipsoid at the predicted time of closest Earth approach. The error ellipsoid is a representation of the scale and orientation of a 3-dimensional Gaussian probability density function. The probability that the object lies in a given region at a given time is simply the integral of the probability density function evaluated at that time over the volume of the region. If we take the region to be the figure of the Earth, this integral evaluation produces the probability that the object's position is within the Earth at the given time. (Here we obviously ignore the dynamics associated with an **impact!)** The result of this integral evaluation, however, is **not** the probability of impact, because it does not take into account the motion of the error ellipsoid past the Earth. The impact probability is the probability that the object's position will at any time lie within the figure of the Earth as it sweeps by the ellipsoid.

The element of time maybe removed from the impact probability computation by projecting the error ellipsoid into the plane perpendicular to the velocity vector of the Earth relative to the object. We will refer to this plane as the "impact" plane. The error ellipsoid then becomes an error ellipse which represents the marginal probability density function describing the probability that the object will at some time pass through a given point on the impact plane. To first order, the figure of the Earth projects into a circle in this plane; the probability of Earth impact is computed by simply integrating the marginal probability density function over the area of this circle.

This problem of computing impact probabilities has been addressed in the past in the context of spacecraft studies motivated by requirements for planetary quarantine and avoidance of impact for spacecraft carrying nuclear materials, Efficient numerical techniques have already been developed for computing impact probabilities via the above procedure (see, e.g., Light 1965; **Michel** 1977). We are not aware of a previous application of this problem to natural bodies.

To be sure, the above method for computing impact probabilities is only an approximation. It considers only linear variations about the predicted trajectory of the object, and so ignores differential perturbations. A more precise computation of impact probabilities could be obtained from a Monte Carlo approach, which would require a great deal more computation.

V. Summary and Conclusions

It is interesting to note that approximately one third of all near-Earth objects are discovered near the closest Earth approach that they will experience in the next 200 years.

This fact underscores the importance of rapidly following up new discoveries with observations (both passive and active) to characterize the object's physical characteristics and to refine its orbit. Often, the discovery apparition of a near-Earth object is <u>the</u> best opportunity to observe it for centuries to come.

Although there are no obvious cases where a known near-Earth asteroid or comet will threaten the Earth in the next two centuries, there are a few objects that warrant special attention. The Aten type asteroid 2340 Hathor makes repeated close Earth approaches and because most of its orbit lies within that of the Earth, it is often a difficult object to observe in a dark sky. For both asteroids and comets, there is generally a dramatic increase in their position uncertainties following a close planetary encounter.

Long-period comets are often found on their first trip into the inner solar system. Because of their short observational data intervals, their unmodeled nongravitational effects and the possibility of their approaching the Earth from the direction of the Sun, long-period comets may present the largest unknown in assessing the long-term risk of Earth approaching objects (Marsden and Steel 1993). Fortunately the number of close Earth approaches from these objects appears to be very small compared to the approaches by short periodic near-Earth objects. Even for the short periodic comets, rocket-like outgassing effects and offsets between the observed center-of-light and the comet's true center-of-mass can sometimes introduce large uncertainties in the long-term extrapolation of cometary orbits. In addition, astrometric radar observations that might be expected to help refine its orbit are often difficult because the radar signal can bounce off a debris cloud of particles surrounding the nucleus rather than the nucleus itself, Astrometric radar observations exist only for two short periodic comets, Encke and Grigg-Skjellerup. The uncertainties in the future motions of active short period comets are substantially larger than those for an asteroid with a comparable observational history. While asteroids dominate the list of close Earth approaches in the next two centuries, their motions are relatively predictable when compared to the active comets.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration,

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Table 1. Earth approaches of comets and asteroids to within 100 lunar distances for the interval 1994 - 2001.. The entries, which are given in chronological order, include the object's name, date of closest approach, and close approach distance.

Object	Date (TDB)	CA Dist (AU)
1993 EA	1994 01 8.056	.1543
3361 Orpheus	1994 03 2.455	.1497
4953 1990 Mu	1994 05 30.441	.1418
5604 1992 FE	1994 06 16.740	.1565
2062 Aten	1994 06 20.360	.2514
1620 Geographos	1994 08 25.424	,0333
2100 Ra-Shalom	1994 10 12.945	.1549
1989 VA	1994 11 15.168	,1820
2062 Aten	1995 01 12.072	.1268
2340 Hathor	1995 01 16,274	,1373
1991 OA	1995 05 24.750	.1122
1991 JX	1995 06 9.098	.0341
2062 Aten	1996 01 24.687	.2234
P/Honda-Mrkos -Pajdusakova	1996 02 4.587	.1702
5590 1990 VA	1996 03 31.361	.2253
2063 Bacchus	1996 03 31.670	.0678
1566 Icarus	1996 06 11.315	.1012
4953 1990 Mu	1996 06 16.749	.2499
1685 Toro	1996 08 2.231	.2207
3103 1982 BB	1996 08 6.105	.1151
1991 CS	1996 08 28.419	.0620
1989 RS1	1996 09 16.095	.1958
1989 UQ	1996 10 23.062	.1504
4947 Ninkasi	1996 10 23.190	.2131
4197 1982 TA	1996 10 25.639	.0846
3908 1980 PA	1996 10 27.860	.0613
4179 Toutatis	1996 11 29.955	.0354
1991 VK	1997 01 10.695	.0749
1989 UQ	1997 01 25.215	.2283
1991 CS	1997 02 23.125	.2229
5590 1990 VA	1997 03 10.252	.2069
P/Encke	1997 07 4.840	.1901
3671 Dionysus	1997 07 6.890	.1144
1988 XB	1997 07 8.698	.1080
4034 1986 PA	1997 08 28.607	.2061
2100 Ra-Shalom	1997 09 26.976	.1705
1989 VA	1997 10 24.671	.2404
'2340 Hathor	1997 11 26.252	.2428
2102 Tantalus	1997 12 21.839	.1379
3361 Orpheus	1998 02 12.772	.1668
5590 1990 VA	1998 02 22.130	.2383
1988 EG	1998 02 28.903	.0316

4183 Curio	1998 06 9.683	.2079
1987 OA	1998 08 19.187	.1019
1991 RB	1998 09 18.475	.0401
1865 **Cerberus**	1998 11 24.747	.1634
1989 UR	1998 11 28.689	.0800
1992 SK	1999 03 26.265	.0560
1863 **Antinous**	1999 04 1.615	.1894
1989 ML	1999 04 27.457	.2520
1991 JX	1999 06 2.819	.0500
1989 VA	1999 11 22.013	.1943
1685 Toro	2000 01 27.237	.2426
5604 1992 FE	2000 03 3.480	.2176
1991 **DB**	2000 03 31.423	.1580
1986 JK	2000 07 11.499	.1218
1991 **BB**	2000 07 27.186	.1662
4486 **Mithra**	2000 08 14.365	.0466
4769 **Castalia**	2000 08 15.718	.2460
2100 **Ra-Shalom**	2000 09 6.039	.1896
1991 **CB1**	2000 09 18.630	.2477
2340 Hathor	2000 10 25.249	.1970
4179 **Toutatis**	2000 10 31.188	.0739
4183 Curio	2000 12 22.793	.1427
4688 1980 **WF**	2001 01 3.609	.1701
3362 Khufu	2001 01 3.687	.2174
4034 1986 PA	2001 04 3,047	.1465
3103 1982 **BB**	2001 08 6.314	.1161
1987 **QB**	2001 08 16.760	.1631
1991 FA	2001 12 14.947	.1923
1990 **SP**	2001 12 27.921	.2298
3362 Khufu	2001 12 29.455	.1596

Table 2. Predicted Earth approaches of comets and asteroids to within 10 lunar distances for the interval 2001 - 2200. The entries are given in order of their close approach distances. The quantities in parentheses are the approximate minimum distances between the object's orbit and that of the Earth.

Object		Date (TDB)	CA Dist (AU)	
2340	Hathor	2086 10 21..670	.0057	(0.006)
2340	Hathor	2069 10 21.351	.0066	(0.006)
2101	Adonis	2177 02 9.000	.0072	(0.006)
4660	Nereus	2060 02 14.288	,0080	(0.005)
4179	Toutatis	2004 09 29.568	.0104	(0.006)
4581	Asclepius	2051 03 24.343	.0122	(0.004)
4660	Nereus	2071 02 4.795	.0149	(0.005)
	1991 OA	2070 07 13.675	.0149	(0.003)
3361	Orpheus	2194 04 14.409	.0167	(0.016)
4660	Nereus	2112 12 23.405	.0181	(0.006)
4660	Nereus	2166 02 3.447	.0186	(0.006)
4581	Asclepius	2133 03 25.160	.0187	(0.005)
5011	Ptah	2170 03 23.262	.0191	(0.019)
5011	Ptah	2193 03 18.580	,0193	(0.019)
2101	Adonis	2102 07 10.004	.0195	(0.009)
3362	Khufu	2169 08 22.539	.0197	(0.011)
	1990 0s	2053 11 16.034	.0197	(0.009)
3200	Phaethon	2093 12 14.453	,0198	(0.013)
4179	Toutatis	2069 11 5.704	.0198	(0.007)
	1990 0s	2195 11 10.553	.0208	(0.007)
3362	Khufu	2045 08 22.060	.0209	(0.014)
3361	Orpheus	2091 04 18.951	.0211	(0.016)
3200	Phaethon	2189 12 13.642	.0215	(0.003)
2101	Adonis	2143 07 10.945	.0222	(0.007)
	1990 0s	2125 08 17.796	.0228	(0.007)
4581	Asclepius	2183 03 21.643	.0230	(0.006)
4953	1990 Mu	2058 06 5.426	.0231	(0.023)
2340	Hathor	2130 10 22.963	.0233	(0.005)
	1988 EG	2110 02 28.810	.0236	(0.023)
	1989 JA	2022 05 27.051	.0239	(0.024)
	1988 EG	2041 02 27.799	.0241	(0.024)
2340	Hathor	2045 10 21.341	.0242	(0,006)
4769	Castalia	2046 08 26,817	.0250	(0.022)
	1990 0s	2003 11 11.448	.0250	(0.010)

Table 3. Cometary approaches to within 50 lunar distances of the Earth (0.128 AU) for the interval 1'994 - 2200. The entries, which are given in chronological order, include the comet's name, date of closest approach, and close approach distance. The quantities in parentheses are the approximate minimum distances between the object's orbit and that of the-Earth.

Object	Date (TDB)	CA Dist (AU)	
Schwassmann-Wachmann 3	2006 05 10.688	.0912	(0.054)
Honda-Mrkos- Pajdusakova	2011 08 15.275	.0601	(0.060)
Honda-Mrkos- Pajdusakova	2017 02 11,104	.0864	(0.060)
Wirtanen	2018 12 18.464	.0846	(0.013)
Finlay	2060 10 27.042	.0473	(0.032)
Kowal 2	2060 12 10.766	.0928	(0.063)
Schwassmann-Wachmann 3	2070 06 27.074	.1264	(0.009)
Giacobini-Zinner	2112 10 8.355	.0469	(0.030)
Honda-Mrkos- Pajdusakova	2130 02 18.324	.0756	(0.065)
Tuttle	2130 12 23.972	.0890	(0.089)
Halley	2134 05 8.006	.0881	(0.074)
Tsuchinshan 1	2140 01 26.530	.1211	
Grigg-Skjellerup	2146 04 12.253	.0694	(0.068)
Honda-Mrkos- Pajdusakova	2157 01 29.696	.1203	(0.119)
Denning-Fujikawa	2190 11 20.720	.0985	

Figure 1. An ecliptic plane projection of the orbit of asteroid 4179 Toutatis. The positions of the planets Mercury through Jupiter are denoted for the time of the Earth close approach on December 8, 1992.

Figure 2. Geocentric distance of asteroid 4179 Toutatis over the 1995-2005 time interval. Close Earth approaches occur in late 1996,2000, and 2004.

Figure 3. Position error ellipse information for asteroid 4179 Toutatis at the time of the Earth close approach on September 29, 2004. The ellipses represent the l-sigma position errors in the orbit plane assuming the object's position is predicted using an orbit based only upon optical data through Dec. 11, 1992 (larger ellipse) and assuming a prediction using optical data through Dec. 11, 1992 and radar data through Dec. 18, 1992 (smaller ellipse).

Figure 4. An ecliptic plane projection of the orbit of asteroid 2340 Hathor. The positions of the planets Mercury through Jupiter are denoted for the time of the Earth close approach on October 21,2069.

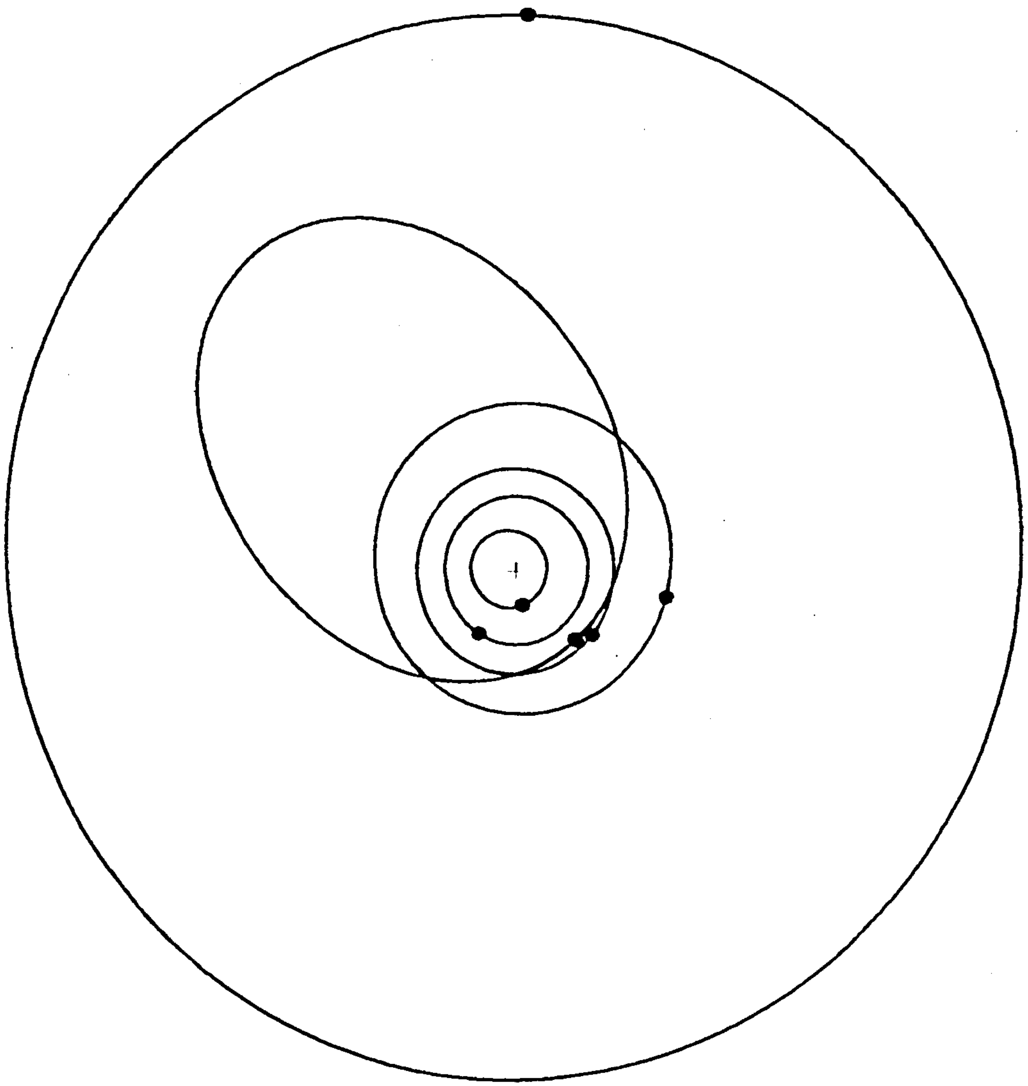
Figure 5. Geocentric distance of asteroid 2340 Hathor over the 2069-2087 time interval. Close Earth approaches occur on October21 in both 2069 and 2087.

Figure 6. One-sigma Earth - Asteroid position uncertainty estimates for asteroid 2340 Hathor over the 2069-2087 interval. Following the 2069 close Earth approach, position errors grow rapidly with time.

Figure 7. An orbital diagram for short periodic comet Finlay. The positions of the planets Mercury through Jupiter are denoted for the time of the Earth close approach on October 27,2060.

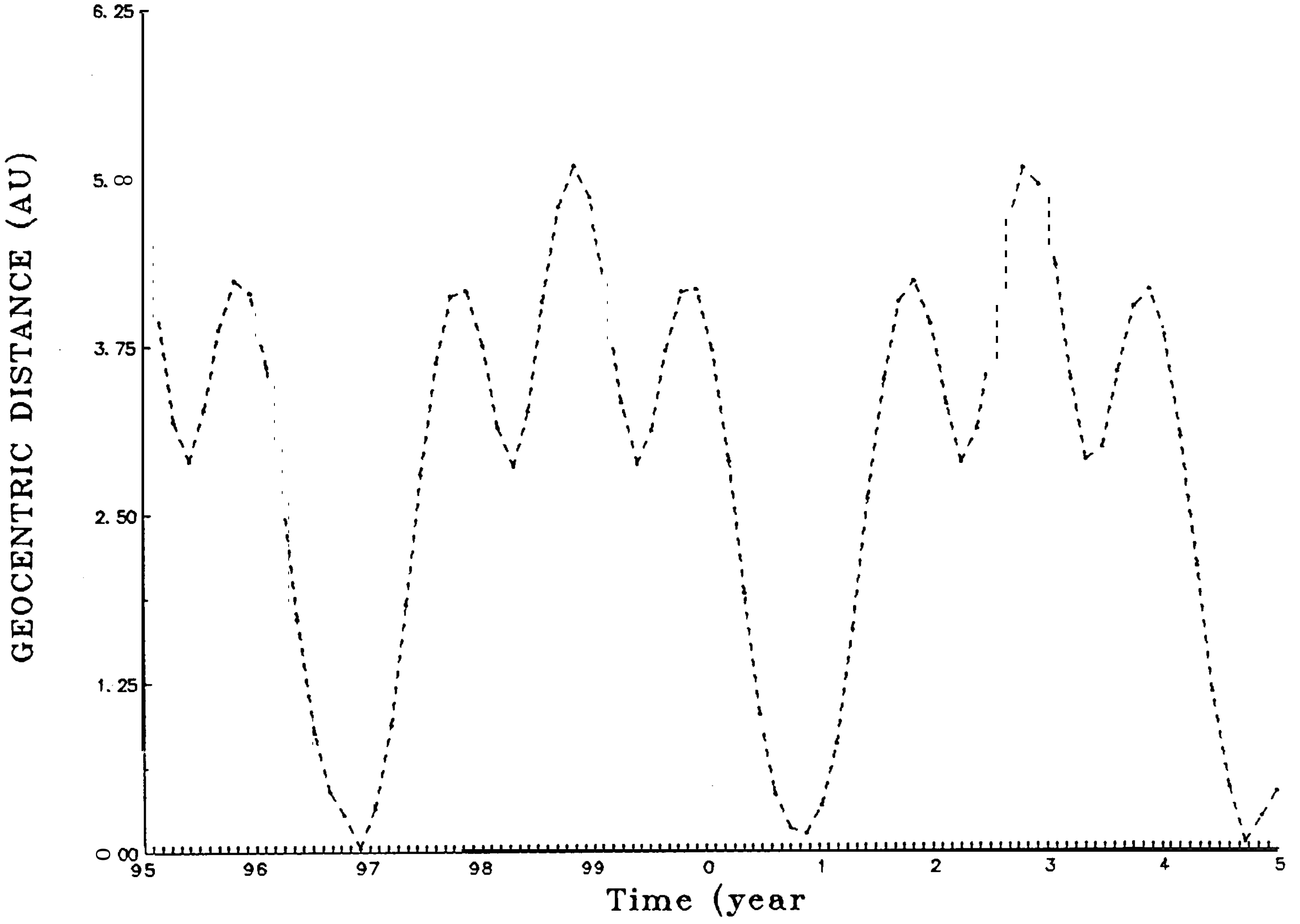
Earth Close Approaches

1992	Dec. 8	0.024 AU
1996	Nov. 29	0.035
2000	Oct. 31	0.074
2004	Sep. 29	0.0[illegible]0

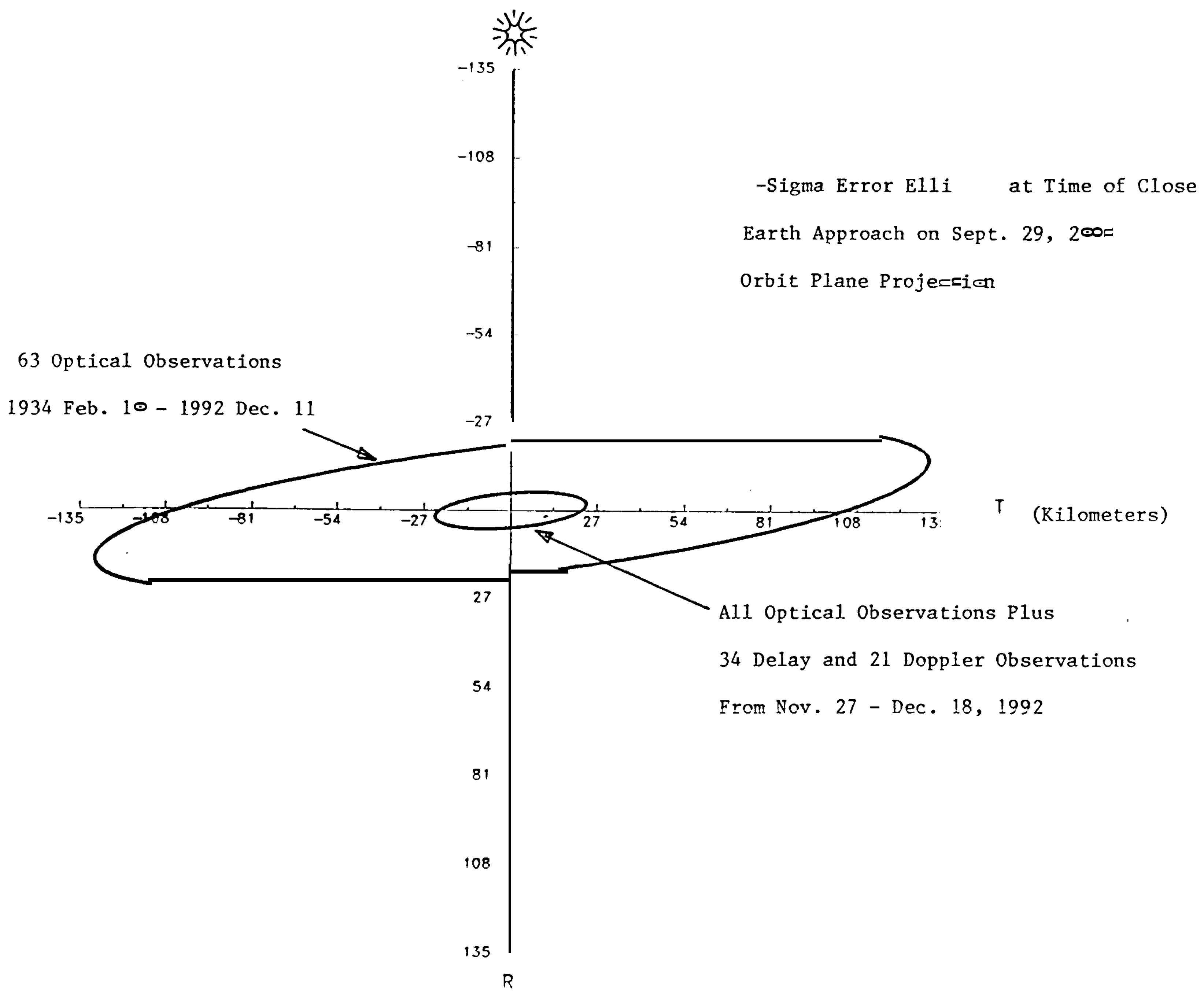


♈

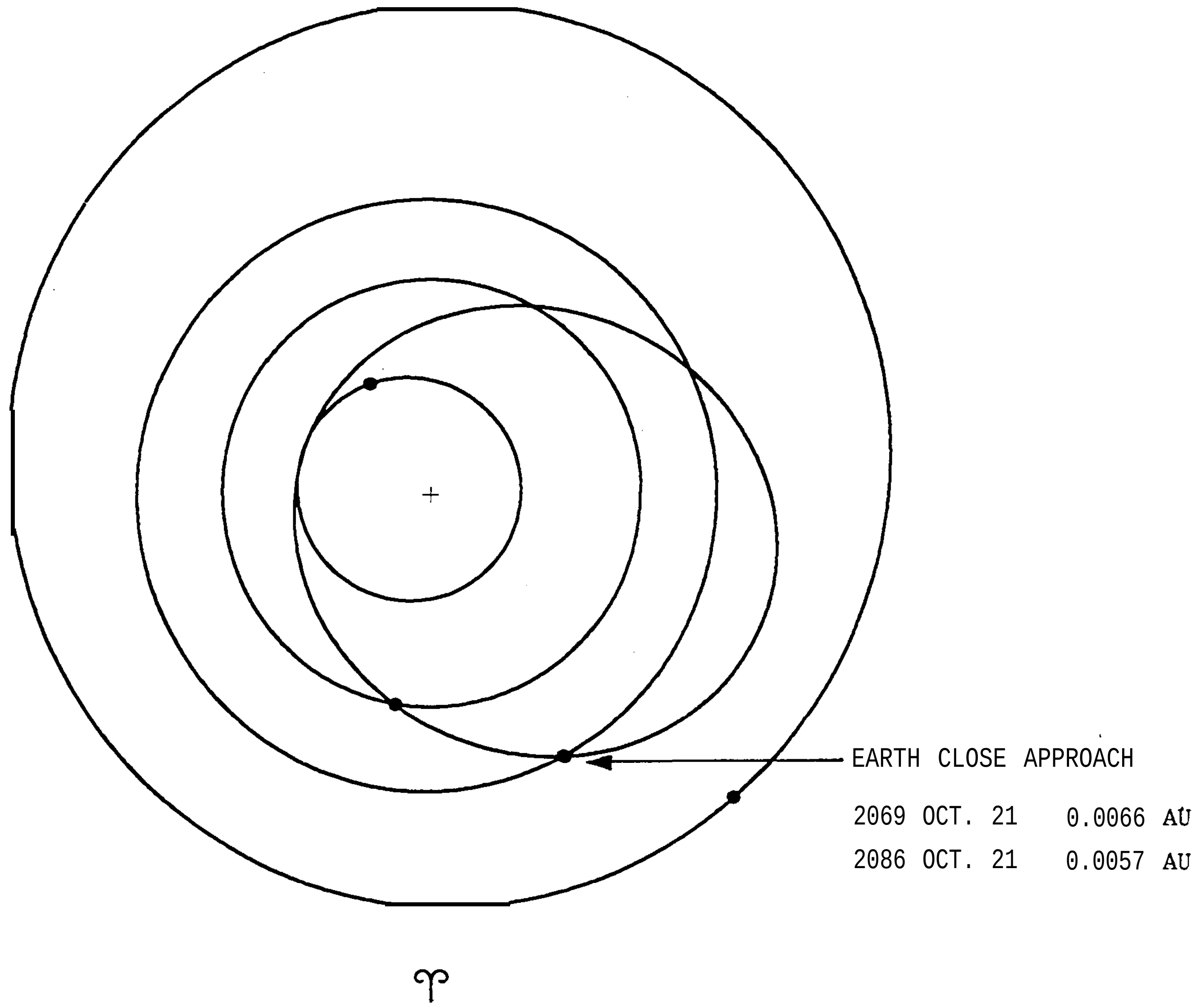
2

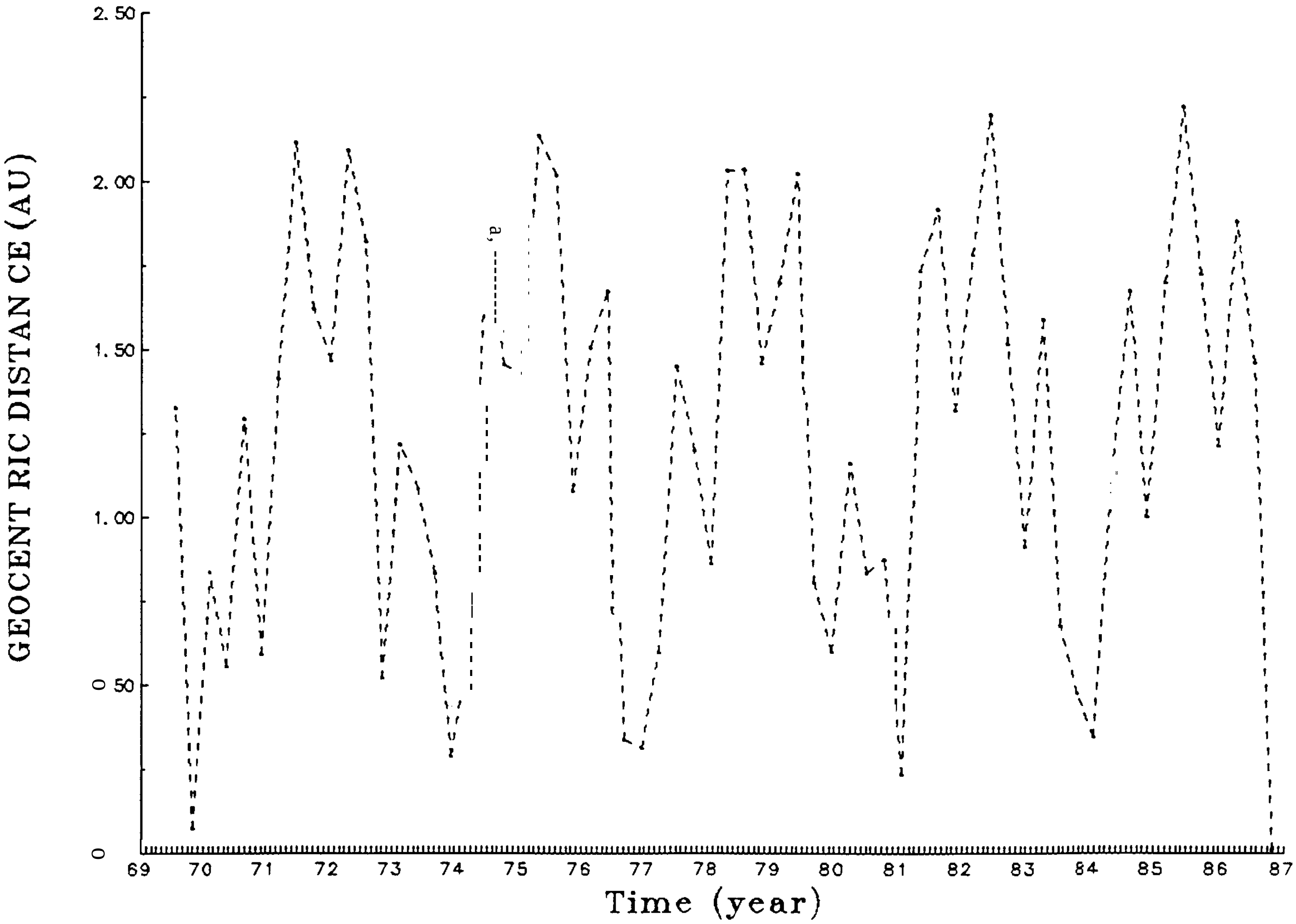


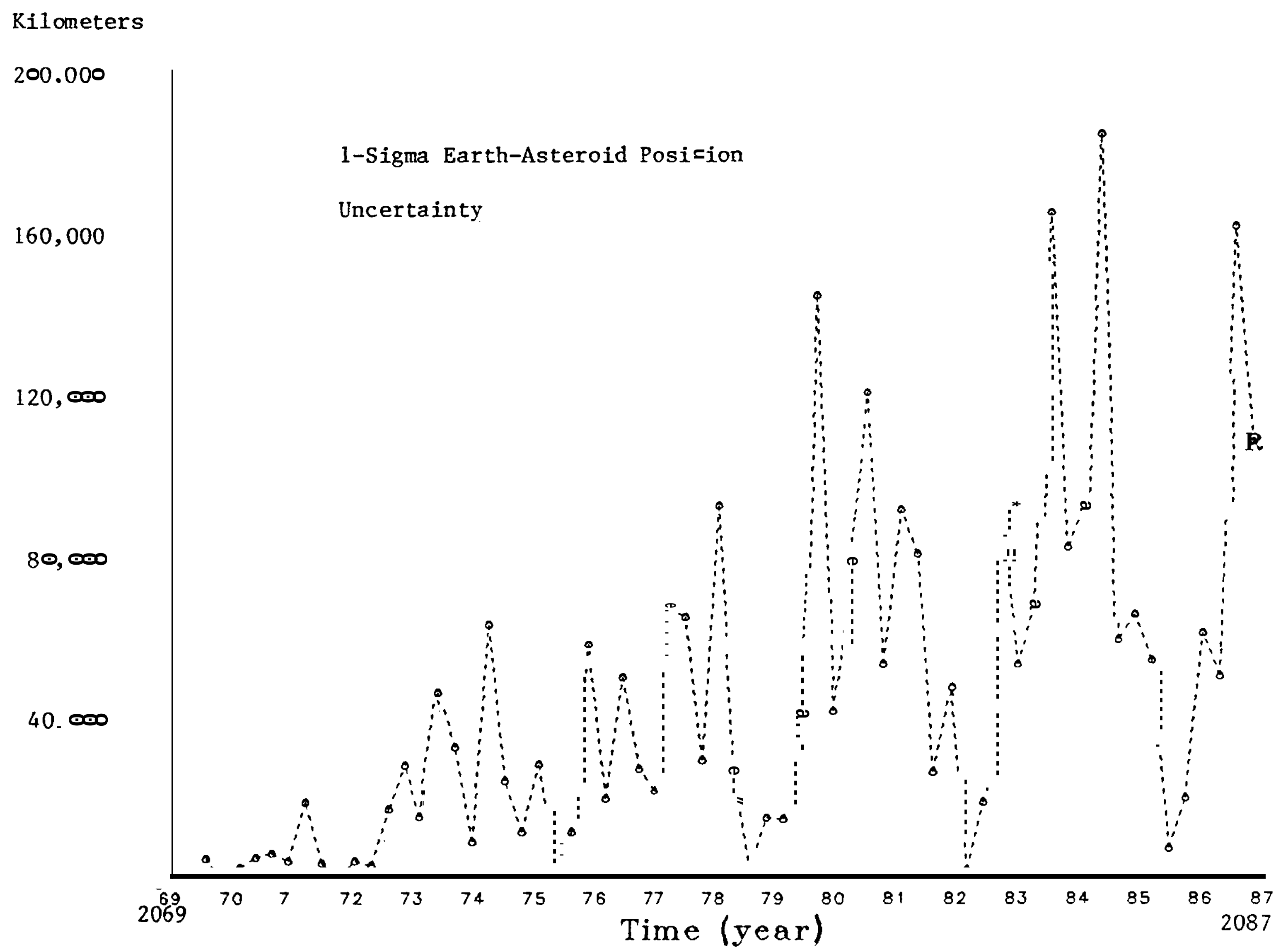
6.25
5.00
3.75
2.50
1.25
0.00
95
96
97
98
99
0
1
2
3
4
5
Time (year
GEOCENTRIC DISTANCE (AU)

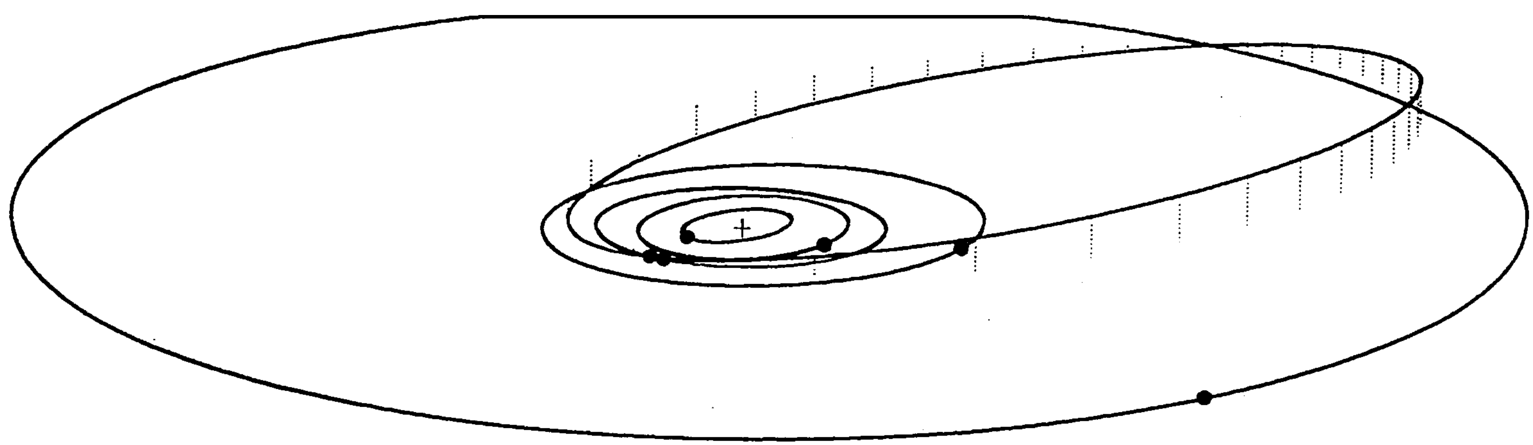


-Sigma Error Elli at Time of Close
Earth Approach on Sept. 29, 2004
Orbit Plane Projection
63 Optical Observations
1934 Feb. 10 - 1992 Dec. 11
All Optical Observations Plus
34 Delay and 21 Doppler Observations
From Nov. 27 - Dec. 18, 1992
T (Kilometers)
R
-135
-108
-81
-54
-27
27
54
81
108
135


EARTH CLOSE APPROACH
2069 OCT. 21 0.0066 AU
2086 OCT. 21 0.0057 AU
♈


GEOCENT RIC DISTAN CE (AU)
2.50
2.00
1.50
1.00
0 50
0
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
Time (year)
a,


Kilometers
200,000
160,000
120,000
80,000
40,000
1-Sigma Earth-Asteroid Position
Uncertainty
69
2069
70
7
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
2087
Time (year)



Close Earth

2060 Oct. 27   0.0473 AU